

Limits on the Ununified Standard Model

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The ununified standard model is an extension of the standard model that contains separate electroweak gauge groups for quarks and leptons. When it was originally proposed, data allowed the new gauge bosons to be quite light. We use recent data from precision electroweak measurements to put stringent bounds on the ununified standard model. In particular, at the 95% confidence level, we find that the ununified gauge bosons must have masses above about 2 TeV.

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1. Introduction

The standard $SU(2) \times U(1)$ electroweak model is in satisfactory agreement with the panoply of data from precision measurements at LEP and SLC as well as low-energy experiments. Numerous extensions to this model predict the existence of extended weak gauge-symmetries and, hence, of additional weak-charged gauge-bosons. However, even prior to the advent of precision measurements at LEP and SLC, the extra gauge-bosons in most such models were constrained to be heavy because of their potential effects on low-energy measurements and on the W and Z masses. One interesting counter-example to this is the ununified standard model [1] which contains separate electroweak gauge groups for quarks and leptons. To a good approximation in this theory the existence of extra weak-charged gauge-bosons *does not* spoil the tree-level relationship between G_F as measured in μ -decay, $\sin^2 \theta_W$ as measured in deep-inelastic ν -scattering, and M_W or M_Z . Hence, those data could accommodate extra states as light as 250 GeV [1].

At the time that the ununified model was proposed, it was anticipated that the model would be more stringently tested by high-energy data such as measurements of Z branching ratios at LEP [1] and measurements of forward-backward asymmetries at LEP and the Tevatron [2]. Indeed, as high-energy data from LEP and HERA became available, the lower bound on the masses of the extra gauge bosons was raised to roughly 500 GeV (the precise value depending on the strength of the mixing between the sets of weak gauge bosons) [3]. Later, Tevatron dijet data was shown to give similar limits [4].

In this note, we re-evaluate limits on the ununified standard model in light of current measurements of precision electroweak observables both at the Z -pole and from low-energies. We perform a global fit to all the data using the techniques of Burgess, *et. al.* [5]. We show that recent LEP data now place a lower bound on the masses of the extra W and Z of order 2 TeV.

The second section of this note reviews the ununified standard model. The third explains the linear approximation used to find the changes in the electroweak observables relative to their standard model values. The last two sections discuss the global fit and the results.

2. The Ununified Standard Model

As described in ref. [1], this model is based on the electroweak gauge group $SU(2)_q \times SU(2)_\ell \times U(1)$. Left-handed quarks and leptons transform as doublets under $SU(2)_q$ and $SU(2)_\ell$, respectively; right-handed quarks and leptons transform as singlets under both $SU(2)$ gauge groups. The $U(1)$ is the hypercharge group of the standard model.¹ The gauge covariant derivative is

$$\partial^\mu + ig_q T_q^a W_{qa}^\mu + ig_\ell T_\ell^a W_{\ell a}^\mu + ig' Y X^\mu, \quad (2.1)$$

where T_q^a and T_ℓ^a , $a = 1$ to 3 , are the $SU(2)$ generators and Y generates hypercharge. The gauge couplings may be written

$$g_q = \frac{e}{\sin \phi \sin \theta_W}, \quad g_\ell = \frac{e}{\cos \phi \sin \theta_W}, \quad g' = \frac{e}{\cos \theta_W}, \quad (2.2)$$

in terms of the usual weak mixing angle θ_W and a new mixing angle ϕ .

The electroweak gauge group spontaneously breaks to $U(1)_{em}$ which is generated by $Q = T_{3q} + T_{3\ell} + Y$. This symmetry breaking occurs when two scalar fields, Φ and $\Sigma = \sigma + i\vec{\tau} \cdot \vec{\pi}$, transforming respectively as $(1, 2)_{1/2}$ and $(2, 2)_0$ acquire the vacuum expectation values (vev's)

$$\langle \Phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \quad \langle \Sigma \rangle = \begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix}. \quad (2.3)$$

The vev of Σ breaks the two $SU(2)$'s down to the diagonal $SU(2)$ of the standard model. Thus this theory reproduces the phenomenology of the standard model for $u \gg v$. What was originally interesting about the model was that $u \approx v$ was permitted by existing data for a wide range of $\sin \phi$.

In order to compare the model with present data, we will need to understand both the form of the four-fermion current-current interactions at zero momentum transfer and the properties of the gauge boson eigenstates. Let us start with the low-energy theory. Putting the matrix of squared vev's in the $\begin{pmatrix} q \\ \ell \end{pmatrix}$ basis,

$$V^2 = \begin{pmatrix} u^2 & -u^2 \\ -u^2 & v^2 + u^2 \end{pmatrix} \quad (2.4)$$

¹ See [1] for comments on the use of additional fermions to cancel the $SU(2)_q^2 \times U(1)$ and $SU(2)_\ell^2 \times U(1)$ anomalies.

and writing the left-handed charged quark and lepton currents as j_q^μ and j_ℓ^μ , one finds the charged current four-fermion weak interactions

$$\frac{2}{v^2} (j_q + j_\ell)^2 + \frac{2}{u^2} j_q^2 . \quad (2.5)$$

Because the non-leptonic weak interactions are enhanced by a factor $(1 + v^2/u^2)$ relative to the leptonic and semi-leptonic weak interactions, the value of $v^2/u^2 \equiv 1/x$ must be less than 1. In studying this theory at energies below the weak scale, it is therefore possible to use an effective theory corresponding to the standard model plus corrections of order $1/x$.

Similarly, in terms of the neutral left-handed T_3 currents j_{3q}^μ and $j_{3\ell}^\mu$ and the full electromagnetic current j_{em}^μ the four-fermion neutral current interactions are

$$\frac{2}{v^2} (j_{3q}^\mu + j_{3\ell}^\mu - j_{em}^\mu \sin^2 \theta_W)^2 + \frac{2}{u^2} (j_{3q}^\mu - j_{em}^\mu \sin^2 \phi \sin^2 \theta_W)^2 . \quad (2.6)$$

Again, the first term has the same form as the neutral current interactions of the standard model and the second term enhances nonleptonic neutral currents. What is different is that the second term also contains new semileptonic and leptonic vectorial interactions which vanish as $\sin^2 \phi \rightarrow 0$. Neutrino neutral currents and the axial coupling of charged leptons are unaffected.

Next, we turn to the gauge boson eigenstates. It is convenient [1] to rewrite the gauge bosons in the following basis

$$W_1^{\pm\mu} = s W_q^{\pm\mu} + c W_\ell^{\pm\mu} , \quad W_2^{\pm\mu} = c W_q^{\pm\mu} - s W_\ell^{\pm\mu} \quad (2.7)$$

$$Z_1^\mu = \cos \theta_W (s W_{3q}^\mu + c W_{3\ell}^\mu) - \sin \theta_W X^\mu , \quad Z_2^\mu = c W_{3q}^\mu - s W_{3\ell}^\mu \quad (2.8)$$

where W_1 and Z_1 are the standard model gauge bosons, $s \equiv \sin \phi$, and $c \equiv \cos \phi$. Then in the limit that $1/x$ is less than 1, we can obtain perturbative expressions for the masses of the light eigenstates

$$\frac{M_W^L}{M_W^0} \approx \frac{M_Z^L}{M_Z^0} \approx \left(1 - \frac{s^4}{2x}\right) , \quad (2.9)$$

where M_W^0 and M_Z^0 are the tree level gauge boson masses in the standard model. Note that, if s^2 is small as well as $1/x$, the corrections to the masses are small. In the small $1/x$ limit the light states are

$$W^L \approx W_1 + \frac{s^3 c}{x} W_2 , \quad Z^L \approx Z_1 + \frac{s^3 c}{x \cos \theta_W} Z_2 . \quad (2.10)$$

and they couple to fermions as, respectively,

$$\frac{e}{\sin \theta_W} \left(T_q^\pm + T_\ell^\pm + \frac{s^2}{x} (c^2 T_q^\pm - s^2 T_\ell^\pm) \right) \quad (2.11)$$

$$\frac{e}{\sin \theta_W \cos \theta_W} \left(T_{3q} + T_{3\ell} - \sin^2 \theta_W Q + \frac{s^2}{x} (c^2 T_{3q} - s^2 T_{3\ell}) \right). \quad (2.12)$$

In this approximation, the heavy eigenstates have a mass given by

$$\frac{M_W^H}{M_W^0} \approx \frac{M_Z^H}{M_Z^0} \approx \frac{\sqrt{x}}{sc} \left(1 + \frac{s^4}{2x} \right). \quad (2.13)$$

3. Changes in Physical Observables

At lowest-order, the predictions for electroweak observables in the standard model depend only on the measured values of $\alpha_{em}(M_Z)$, G_F , and M_Z . In the ununified model, the lowest-order predictions will also depend on the values of s^2 and $1/x$. To constrain s^2 and $1/x$, one should fit the observed values of the precisely measured electroweak quantities to their predicted values in the ununified model and determine the allowed values of s^2 and $1/x$.

In practice we know that the standard model is at least approximately correct and we expect that $1/x$ is small. Therefore, as we have done in the previous section, we will calculate the values of electroweak observables to leading order in $1/x$. Using the expressions given in the previous section, we may evaluate the changes in various physical observables relative to their standard model values to first-order in $1/x$ [5]. We obtain the following expressions for these changes:

$$\Gamma_Z = \Gamma_Z^{SM} \left(1 + \frac{1}{x} [0.732s^4 + 1.634s^2c^2] \right), \quad (3.1)$$

$$R_\ell = \frac{\Gamma_h}{\Gamma_\ell} = R_\ell^{SM} \left(1 + \frac{1}{x} [2.405s^4 + 2.337s^2c^2] \right), \quad (3.2)$$

$$\sigma_h = \frac{12\pi\Gamma_e\Gamma_h}{M_Z^2\Gamma_Z^2} = \sigma_h^{SM} \left(1 + \frac{1}{x} [-0.931s^4 - 0.931s^2c^2] \right), \quad (3.3)$$

$$R_b = \frac{\Gamma_b}{\Gamma_h} = R_b^{SM} \left(1 + \frac{1}{x} [-0.059s^4 - 0.052s^2c^2] \right), \quad (3.4)$$

$$A_{FB}^\ell = A_{FB}^{\ell, SM} + \frac{1}{x} [0.184s^4] , \quad (3.5)$$

$$A_{FB}^b = A_{FB}^{b, SM} + \frac{1}{x} [0.559s^4 + 0.017s^2c^2] , \quad (3.6)$$

$$A_{FB}^c = A_{FB}^{c, SM} + \frac{1}{x} [0.525s^4 + 0.094s^2c^2] , \quad (3.7)$$

$$A_{LR} = A_e = A_{LR}^{SM} + \frac{1}{x} [0.769s^4] , \quad (3.8)$$

$$A_\tau(P_\tau) = A_{pol}^{SM}(\tau) + \frac{1}{x} [0.769s^4] , \quad (3.9)$$

$$A_e(P_\tau) = A_e^{SM}(P_\tau) + \frac{1}{x} [0.769s^4] , \quad (3.10)$$

$$M_W = M_W^{SM} \left(1 + \frac{1}{x} [0.213s^4] \right) , \quad (3.11)$$

$$\frac{M_W}{M_Z} = \frac{M_W^{SM}}{M_Z^{SM}} \left(1 + \frac{1}{x} [0.213s^4] \right) , \quad (3.12)$$

$$g_L^2(\nu N \rightarrow \mu^- X) = (g_L^2)^{SM} + \frac{1}{x} [0.244s^4] , \quad (3.13)$$

$$g_R^2(\nu N \rightarrow \mu^- X) = (g_R^2)^{SM} + \frac{1}{x} [-0.085s^4] , \quad (3.14)$$

$$g_{eV}(\nu e \rightarrow \nu e) = g_{eV}^{SM} + \frac{1}{x} [-0.656s^4] , \quad (3.15)$$

$$g_{eA}(\nu e \rightarrow \nu e) = g_{eA}^{SM} , \quad (3.16)$$

$$Q_W(^{135}_{55}Cs) = Q_W^{SM} + \frac{1}{x} [-1.45s^4] . \quad (3.17)$$

Where

$$A_{FB}^f = \frac{3}{4} A_e A_f , \quad (3.18)$$

$$A_f = \frac{2g_V^f g_A^f}{\left(g_V^f\right)^2 + \left(g_A^f\right)^2} , \quad (3.19)$$

$$g_V^f = T_3 - 2Q \sin^2 \theta_W , \quad (3.20)$$

and

$$g_A^f = T_3 . \quad (3.21)$$

Using the current experimental values of the electroweak observables and using the corresponding best-fit *standard model* predictions, we may use the equations above to fit the ununified model predictions to the data.

4. Global Fit

Before proceeding with the fit and determining the allowed values of s^2 and $1/x$, we must discuss the issue of higher-order corrections. At higher-order, the predictions of the standard or ununified models also depend² on the values of $\alpha_s(M_Z)$ and the top-quark mass m_t . Given the success of the standard model, we expect that, for the allowed range of s^2 and $1/x$, the changes in the predicted values of physical observables due to radiative corrections in the standard or ununified model will be approximately the same *for the same values of $\alpha_s(M_Z)$ and m_t* .

The best-fit standard model predictions which we use [6] are based on a top quark mass of 173 GeV (taken from a fit to precision electroweak data) which, fortuitously, is consistent with the range of masses (174 ± 16 GeV) preferred by observed top-candidate events at CDF [7].

The treatment of $\alpha_s(M_Z)$ is more problematic: the LEP determination for $\alpha_s(M_Z)$ comes from a *fit* to electroweak observables *assuming* the validity of the standard model. For this reason, as emphasized by Erler and Langacker [8], when analyzing non-standard models it is important to understand how the bounds vary for different values of $\alpha_s(M_Z)$. We present results for bounds on s^2 and $1/x$ both for $\alpha_s(M_Z) = 0.124$ (which is the LEP best-fit value assuming the standard model is correct [6]) and for $\alpha_s(M_Z) = 0.115$ as suggested by recent lattice results [9] and deep-inelastic scattering [6][10]. To the accuracy

² The predictions also depend to a lesser extent on the mass of the Higgs boson and, for the ununified model, the Φ and Σ masses. At the present level of experimental accuracy, this dependence is not numerically significant.

to which we work, the α_s dependence of the standard model predictions only appears in the Z partial widths (we neglect the effect of the uncertainty in α_s in the forward-backward asymmetries since this effect is small compared to the experimental errors [11]), and we use [6]

$$\Gamma_q = \Gamma_q|_{\alpha_s=0} \left(1 + \frac{\alpha_s}{\pi} + 1.409 \left(\frac{\alpha_s}{\pi} \right)^2 - 12.77 \left(\frac{\alpha_s}{\pi} \right)^3 \right) \quad (4.1)$$

to obtain the standard model predictions for $\alpha(M_Z) = 0.115$.

We perform a global fit [5] for the parameters of the ununified model to all precision electroweak data: the Z line shape, forward backward asymmetries, τ polarization, and left-right asymmetry measured at LEP and SLC; the W mass measured at FNAL and UA2; the electron and neutrino neutral current couplings determined by deep-inelastic scattering; and the degree of atomic parity violation measured in Cesium. Care was taken *not* to use a Pentium based computer [12]. The experimental values [6][13] of the electroweak observables used and the corresponding standard model predictions [6] are shown in Table 1.

We present results of the fit in terms of limits on the mass of the heavy W gauge boson, M_W^H (which is lighter than M_Z^H by a factor of $\cos \theta_W$), as a function of the mixing angle s^2 . In figures 1 and 2 we show the 95% (solid) and 90% (dashed) confidence contours in the M_W^H - s^2 plane for $\alpha_s(M_Z) = 0.115$ and 0.124, respectively. In both cases, we find that the lower bound on M_W^H is approximately 2 TeV.

For $\alpha_s = 0.115$ the standard model does not fit the data particularly well. The χ^2/df for the standard model is 1.60, where the number of degrees of freedom (df) is the number of measurements (21 since we are not assuming lepton universality) minus the number of fit parameters (i.e. 0). If the standard model were correct, then there would be a 4% probability that the fit would be this bad or worse.

In contrast, for $\alpha_s = 0.115$ in the ununified model (with $s^2 = 0.5$) we find $\chi^2/\text{df} = 1.39$ with $\text{df} = 20$. If the ununified model were correct, the probability of a fit this bad or worse would be 11%, making the ununified model a *better* fit to the data. Furthermore, the standard model actually lies outside of the 95% confidence region surrounding the best fit for M_W^H . This results in the upper set of curves in the M_W^H - s^2 plane – an upper bound on M_W^H as a function of the mixing angle. The best fit for the heavy W mass is $M_W^H = 2.9^{+0.9}_{-0.5} \text{ TeV}$.

For $\alpha_s = 0.124$ the standard model fit improves considerably. The χ^2/df for the standard model is 1.38 (here $\text{df} = 20$ for both models, since $\alpha_s(M_Z)$ is a fit parameter

Quantity	Experiment	SM	Ununified
Γ_Z	2.4976 ± 0.0038	2.4923	2.4969
R_e	20.86 ± 0.07	20.731	20.807
R_μ	20.82 ± 0.06	20.731	20.807
R_τ	20.75 ± 0.07	20.731	20.807
σ_h	41.49 ± 0.11	41.50	41.44
R_b	0.2202 ± 0.0020	0.2155	0.2155
A_{FB}^e	0.0156 ± 0.0034	0.016	0.016
A_{FB}^μ	0.0143 ± 0.0021	0.016	0.016
A_{FB}^τ	0.0230 ± 0.0026	0.016	0.016
$A_\tau(P_\tau)$	0.143 ± 0.010	0.146	0.147
$A_e(P_\tau)$	0.135 ± 0.011	0.146	0.147
A_{FB}^b	0.0967 ± 0.0038	0.1026	0.1030
A_{FB}^c	0.0760 ± 0.0091	0.073	0.074
A_{LR}	0.1637 ± 0.0075	0.146	0.147
M_W	80.17 ± 0.18	80.34	80.35
M_W/M_Z	0.8813 ± 0.0041	0.8810	0.8811
$g_L^2(\nu N \rightarrow \nu X)$	0.3003 ± 0.0039	0.303	0.303
$g_R^2(\nu N \rightarrow \nu X)$	0.0323 ± 0.0033	0.030	0.030
$g_{eA}(\nu e \rightarrow \nu e)$	-0.503 ± 0.018	-0.506	-0.506
$g_{eV}(\nu e \rightarrow \nu e)$	-0.025 ± 0.019	-0.039	-0.040
$Q_W(^{135}_{55}Cs)$	-71.04 ± 1.81	-72.78	-72.78

Table 1: Experimental [6][13] and predicted values of electroweak observables for the standard model and ununified standard model for $\alpha_s(M_Z) = 0.115$ and (for the ununified model) $s^2 = 0.5$. The standard model values correspond to the best-fit values (with $m_t = 173$ GeV, $m_{\text{Higgs}} = 300$ GeV) in [6], corrected for the change in $\alpha_s(M_Z)$, and the revised extraction [14] of $\alpha_{em}(M_Z)$.

for the standard model), while for the ununified model (with $s^2 = 0.5$) one also finds $\chi^2/\text{df} = 1.38$. The probability of a fit with χ^2/df equal to or greater than that observed is 12% for both models. The best fit for the heavy W mass at $s^2 = 0.5$ is $M_W^H = 7.8^{+\infty}_{-3.9}$ TeV. The values of the electroweak observables used and the corresponding model predictions are shown in Table 2.

Quantity	Experiment	SM	Ununified
Γ_Z	2.4976 ± 0.0038	2.4974	2.4980
R_e	20.86 ± 0.07	20.791	20.802
R_μ	20.82 ± 0.06	20.791	20.802
R_τ	20.75 ± 0.07	20.791	20.802
σ_h	41.49 ± 0.11	41.45	41.44
R_b	0.2202 ± 0.0020	0.2155	0.2155
A_{FB}^e	0.0156 ± 0.0034	0.016	0.016
A_{FB}^μ	0.0143 ± 0.0021	0.016	0.016
A_{FB}^τ	0.0230 ± 0.0026	0.016	0.016
$A_\tau(P_\tau)$	0.143 ± 0.010	0.146	0.146
$A_e(P_\tau)$	0.135 ± 0.011	0.146	0.146
A_{FB}^b	0.0967 ± 0.0038	0.1026	0.1027
A_{FB}^c	0.0760 ± 0.0091	0.073	0.073
A_{LR}	0.1637 ± 0.0075	0.146	0.146
M_W	80.17 ± 0.18	80.34	80.34
M_W/M_Z	0.8813 ± 0.0041	0.8810	0.8810
$g_L^2(\nu N \rightarrow \nu X)$	0.3003 ± 0.0039	0.303	0.303
$g_R^2(\nu N \rightarrow \nu X)$	0.0323 ± 0.0033	0.030	0.030
$g_{eA}(\nu e \rightarrow \nu e)$	-0.503 ± 0.018	-0.506	-0.506
$g_{eV}(\nu e \rightarrow \nu e)$	-0.025 ± 0.019	-0.039	-0.039
$Q_W(^{135}_{55}Cs)$	-71.04 ± 1.81	-72.78	-72.78

Table 2: Experimental [6][13] and predicted values of electroweak observables for the standard model and ununified standard model for $\alpha_s(M_Z) = 0.124$ and (for the ununified model) $s^2 = 0.5$. The standard model values correspond to the best-fit values (with $m_t = 173$ GeV, $m_{\text{Higgs}} = 300$ GeV) in [6], corrected for the revised extraction [14] of $\alpha_{em}(M_Z)$.

5. Discussion

The ununified standard model provides a novel extension of the usual $SU(2) \times U(1)$ gauge sector in which, at high-energies, leptons and quarks transform under different weak $SU(2)$ gauge groups. In this note we have presented limits on the ununified standard model derived from a global fit to all precision electroweak data. We find that the model is now tightly constrained. In particular, at the 95% confidence level, the lower bound on the mass of the heavy W and Z is approximately 2 TeV.

Heavy W and Z bosons weighing a few TeV should be visible at the LHC in leptonic decay modes. Since the heavy gauge bosons couple to quarks with strength proportional to c/s and to leptons as s/c , the Drell-Yan cross-section (for small s) on the heavy boson resonance would be of order $(s/c)^4$ [1]. The fact that the masses of the heavy W and Z are related by a factor of $\cos \theta_W$ (2.13) would help identify the gauge bosons as belonging to the ununified standard model even if the bosons were so heavy or s were so small that a mere handful of events was observed. The lower bound we have obtained on the masses of the heavy W and Z implies that these bosons are too massive to be produced at proposed electron-positron colliders. Were a sufficiently energetic electron-positron machine to be constructed, one would, correspondingly, expect the heavy W and Z to be visible in hadronic modes rather than leptonic ones.

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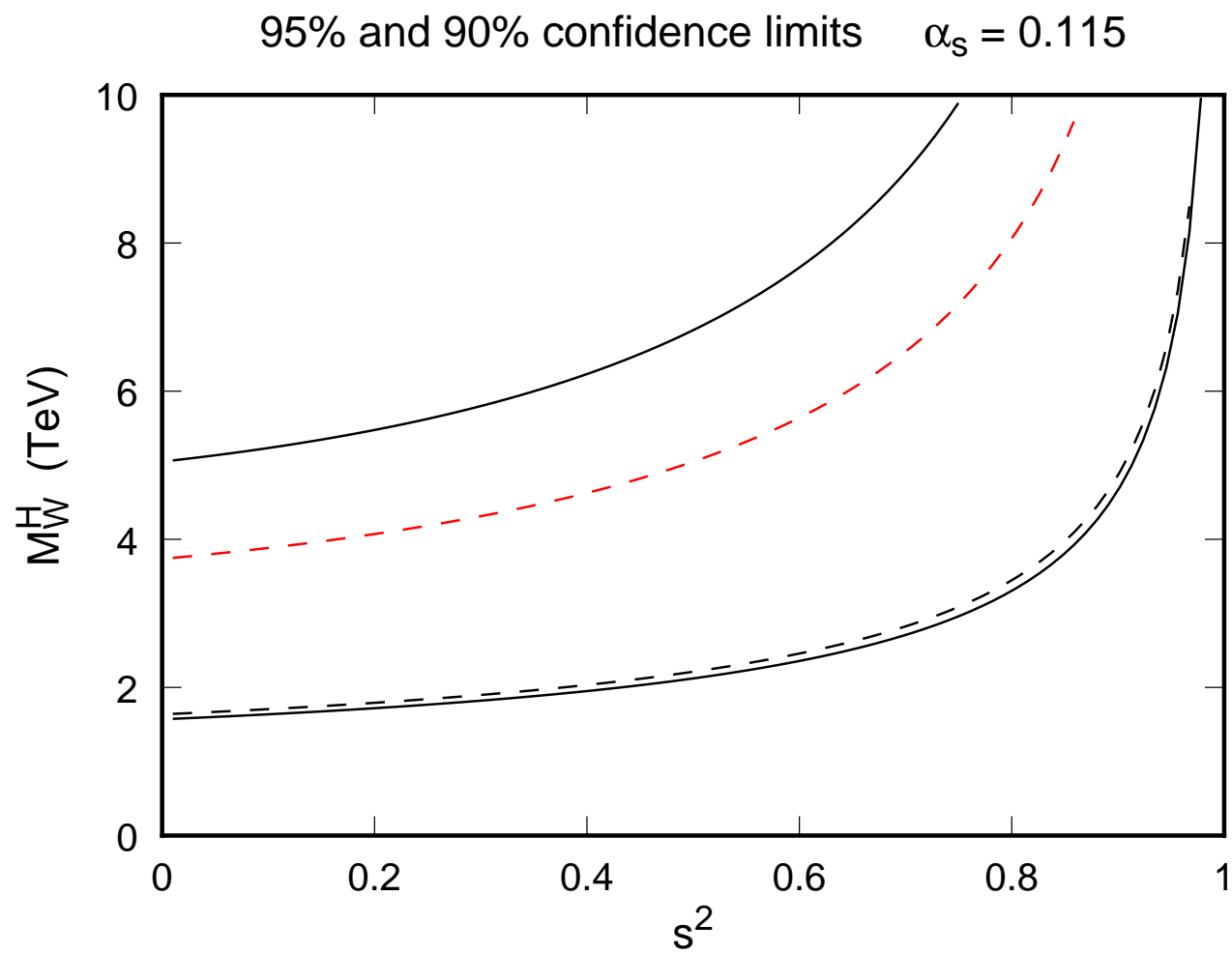
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Figure Captions

Figure 1 90% (dashed) and 95% (solid) bounds on the mass of the heavy W gauge-boson of the ununified standard model (M_W^H) as a function of s^2 for $\alpha_s(M_Z) = 0.115$. The allowed region (at the specified confidence level) is between the curves.

Figure 2 90% (dashed) and 95% (solid) bounds on the mass of the heavy W gauge-boson of the ununified standard model (M_W^H) as a function of s^2 for $\alpha_s(M_Z) = 0.124$. The allowed region (at the specified confidence level) is above the curve.



90% and 95% confidence limits, $\alpha_s = 0.124$

